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SURVIVAL OF TERRESTRIAL PLANETS IN THE PRESENCE OF GIANT PLANET MIGRATION

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ABSTRACT

The presence of "Hot Jupiters", Jovian-mass planets with very short orbital periods orbiting nearby main sequence stars, has been proposed to be primarily due to the orbital migration of planets formed in orbits initially much further from the parent star. This migration affects the evolution of inner terrestrial planets in these systems. Previous analyses have assumed that no terrestrial planets survive after migration has occurred. We present numerical simulations showing that a significant fraction of terrestrial planets could survive the migration process, and possibly return to near circular orbits relatively close to their original positions. A fraction of the final orbits are in the Habitable Zone, suggesting that planetary systems with close-in giant planets are viable targets for searches for Earth-like habitable planets around other stars.

Subject headings: planetary systems:formation and evolution

1.

Over 100 extra-solar planets have been observed (Schneider 2003), and more discoveries are announced each month. The existence of giant planets at very small orbital radii from their host stars was one of the major surprises that has emerged from these detections (Mayor & Queloz 1995). As long-duration studies increase their sensitivity to long-period planets, there remains a significant accumulation of planets in circular orbits at distances $\lesssim 0.25$ AU. Though current detection techniques are biased towards massive planets in close orbits, this pile-up at small distances appears to be genuine.

Current theories postulate several different mechanisms to explain the phenomena of giant planets with small orbital radii. It is generally believed that these planets formed at larger distances either in the conventional model of coalescence of planetesimals to form a core onto which gas accreted (Pollack et al. 1996) or by direct gravitational collapse due to instabilities in the disk (Boss 2001; Mayer et al. 2002) and then migrated inwards due to one, or more, of the following processes: "early migration" involving tidal interaction with the evolving circumstellar disk (Lin et al. 1996), or "late migration" involving planetesimal scattering (Murray et al. 1998) and/or gravitational scattering with other planets (Weidenschilling & Marzari 1996; Rasio & Ford 1996). Gravitational scattering alone cannot account for the shortest period Jovian-type planets in circular orbits, so dissipative migration must occur in some systems. Models suggest that migration processes are an inherent result of disk-planet interactions, and time scales for the duration of migration, after formation of the most massive planet, range from 10^5 to 10^6 years, decreasing as initial disk mass increases and the initial planet formation distance decreases (Trilling et al. 2002). A number of studies have explored the dynamical stability of terrestrial-sized bodies in systems with close-in giant planets. Menou & Tabachnik (2003) performed an exhaustive examination of all detected systems, concluding that at least 25% of systems permit stable terrestrial planets in the Habitable Zone (Kasting et al. 1993) of their star, and considerably more allow a low-mass planet outside of the conventional habitable parameter space. However, the dynamical effects of migration on existing terrestrial planets have not been examined in depth.

Terrestrial planet formation is thought to occur in a "runaway growth" scenario, where the larger gravitational cross-section of the largest planetesimals increases the rate of interactions and facilitates the growth of several large cores (Kortenkamp et al. 2001; Chambers 2001). Current dynamical models predict that Mars-sized objects form in the inner system on a time scale of order 10^5 years and terrestrial planets are fully formed within 30 million years, but recent radioactive dating suggests that our inner Solar System may have formed in as little as 10 million years (Jacobsen 2003; Yin et al. 2002; Kleine et al. 2002). Similarly, time scales for giant planet formation due to core accretion range from 10^6 to 10^7 years (Pollack et al. 1996), with Type II migration beginning after the planet has reached $\sim 10-30M_{\oplus}$ (Lin & Papaloizou 1993); therefore the initial onset of giant planet migration may be relatively slow (10^6 years or greater). This would suggest that substantial terrestrial-sized planetesimals, or "planetary embryos", may already be present in the inner system when giant planet migration begins. Giant planet migration also has profound implications for the evolution of the remaining circumstellar material. Armitage (2003) examined the effect of migration on an initial gas disk, and found that late migration would cause an inward flow of dust-depleted gas which would suppress late terrestrial planet formation. However, the author did not consider the dynamical effects on any planetesimals, either within the migration radius or outside of it. Thébault et al. (2002) examined the effect that several different giant planet systems with unusual properties (high eccentricity, multiple planets) would have on terrestrial planet formation, but did not address migration at all.

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To investigate the potential effects of giant planet migration on a nascent system of terrestrial planets, we have constructed a set of dynamical planetary system models using a hybrid symplectic integrator modified to include artificial giant planet migration. The current simulations assume that a giant planet is relatively close to its final mass before it begins to migrate, and the terrestrial planets are at a substantial fraction of their final mass. Since the details of planetary evolution in systems which experience Jovian migration are currently largely unconstrained, the assumptions included in these simulations may need to be modified for future work, especially if the time scales for terrestrial and giant planet formation prove to be radically different. However, examining the general dynamical evolution of this simple model should help to define the basic parameters of the problem and illuminate interesting areas for future study.

Numerical simulations were performed using a modified version of the publicly-available hybrid symplectic integrator package MERCURY by Chambers & Migliorini (Chambers & Migliorini 1997; Chambers 1999). To examine the effects of migration, we modified the integrator to accommodate a secular decrease in the semi-major axis of a giant planet. With each time step, the coordinates were adjusted so that the planet would move in towards the star at the specified rate. Since the model migration is included by fiat, not through internal physically motivated processes, the system is no longer energy conserving, but the forced change in orbital parameters over each time step for a migration time scale of 10^6 is small, and integration parameters set for a stationary system provide accurate integration of the planets' interactions. The mechanism for migration is not important in these simulations since we are purely investigating the effects of a migrating Jupiter on terrestrial planets at different times. In future simulations, a more physical mechanism for migration may be introduced to more fully analyze effects on the giant planet itself.

The possibility of Type I migration of the terrestrial bodies due to disk interactions (as described by Ward (1997) and Kortenkamp et al. (2001)) was ignored for the main body of simulations for several reasons. First, Type I migration time scales are rapid (on the order of $10^5(M/M_\oplus)^{-1}$ where M is the mass of the planet (Ward 1997)), so the separations between the giant planet and any terrestrial planets interior to the giant planet (except for objects smaller than $0.1M_\oplus$) would increase and very few terrestrial-Jovian interactions would occur. Any interactions that would occur would be governed by the same stochastic processes as in the non-migrating case since these terrestrial planets would be migrating slower than the Jovian-type planet. Several test runs with Type I migration included confirmed these assumptions; only the smallest planets interacted with the migrating Jupiter, and for these the survival statistics were similar to the simulations without Type I migration. Second, recent results (Nelson & Papaloizou 2003; Laughlin et al. 2003) suggest that for bodies smaller than $\sim 10M_\oplus$ MHD turbulence will cause the motion due to torques from the disk to occur in a random walk, and over long time periods smaller bodies will tend to maintain their average position.

For the investigation of the dynamical evolution of terrestrial-sized bodies, several different configurations of bodies with different masses and radii were used. As a starting point an inner system was set up consisting of four bodies with masses and initial orbital parameters identical to our current inner Solar System, since we have reliable data on that configuration. A planet identical to Jupiter was placed at 5.2 AU and allowed to migrate inwards over three different time scales: 5×10^5, 1×10^6, and 2×10^6 years. In order to avoid uncertainties in the variability of migration rate due to disk properties, a constant migration rate was used to compare different migration time scales, and additional simulations were performed to compare constant migration to a more realistic migration model taken from the literature (Trilling et al. 2002; Lin & Papaloizou 1986). One hundred integrations were performed for each migration time scale using a constant migration rate, and another one hundred integrations were performed using a variable migration rate over 1×10^6 years. The initial anomalies for the four terrestrial planets were randomly selected for each integration. In addition to the above model, simulations were run with three different configurations of non-Solar planetary systems, taken from the simulations of Chambers (2001) for the two shorter migration time scales in order to check the statistical consistency of the general results. Collisions were assumed to be completely inelastic, so impacts absorbed the mass of the smaller body into the larger one. The objects were assumed to be spherical, and radii were calculated using an input density and mass. To avoid excessive integration error for orbits near the Sun, objects were assumed to collide with the Sun if their heliocentric distance fell below 0.1 AU. A timestep of 8 days was used for the integrations, and a Burlirsch-Stoer tolerance of 10^{-11}.

A sample integration plot from the 10^6 yr time scale series of integrations using constant migration is shown in Fig. 1. As expected, strong dynamical evolution of the inner planets is observed. The principal effects of interest here are secular orbital perturbations of the smaller planets due to evolving orbital resonances during the giant planet's movement and close interactions with the giant planet.

As the giant planet migrates inward, it moves through various orbital resonances with the inner planets, and excites large eccentricity oscillations. The semi-major axis of the terrestrial planet often decreases somewhat, and random scatterings of different terrestrial planets due to their mutual interaction during this initial excitation period may cause collisions with the Sun or one of the other planets. In the 10^6 year integration, the planet at initial Earth orbit is particularly susceptible to resonances with the giant planet, typically locking into a 3:1 resonance and migrating with the giant planet until it is perturbed by the Venus analog. If a terrestrial planet survives the initial perturbation until the giant planet is in a relatively close orbit, then direct interaction with the giant planet will dominate the next stage of evolution. The outcome is typically a slingshot encounter, where the terrestrial planet is impelled outwards and its eccentricity, semi-major axis, and orbital period increase sharply.[1] The

[1] If a terrestrial planet is initially in a near-circular orbit with semi-major axis a_i, it will generally only suffer a large impulsive perturbation to its orbital elements if it comes within the "Hill" radius of influence, $r_H = 3\sqrt[3]{m_J/M_*}$ of the Jovian, where m_J

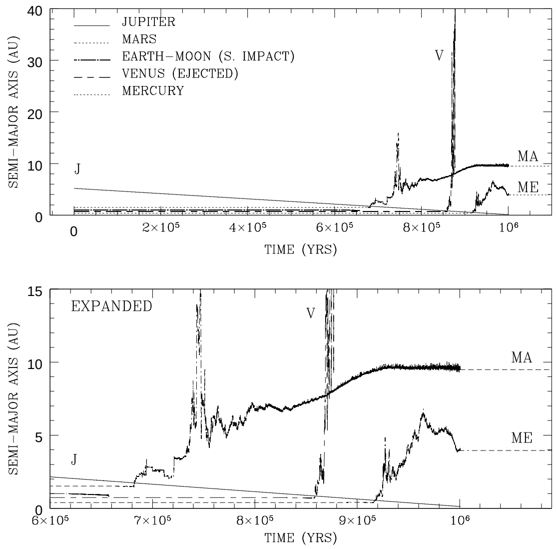

FIG. 1.— Graph of semi-major axis vs. time for a sample integration with a migration time scale of 1×10^6 yr. The final semi-major axis of bound planets is shown as a dotted line. Interactions during migration result in impacts with the central star, planet-planet impacts, ejection from the system, or simply eccentricity enhancement. A significant fraction of scattered planets remain bound, and dynamical friction may cause the orbits of these planets to re-circularize.

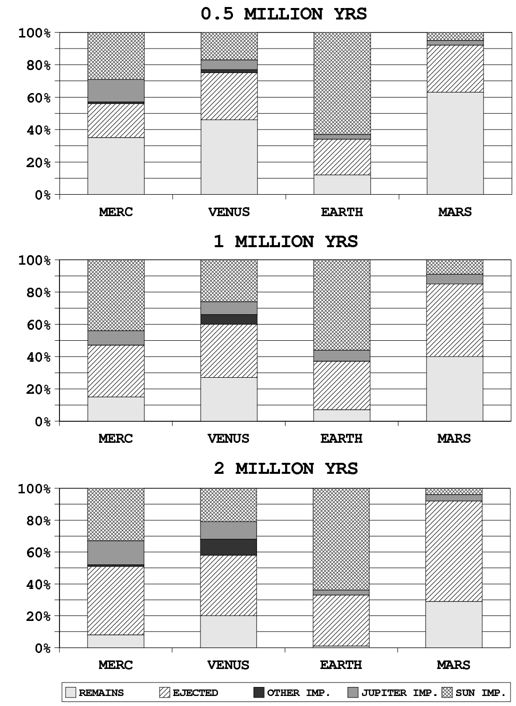

FIG. 2.— Final distributions of the fate of the four terrestrial planets for each of the three migration time scales using a Solar System terrestrial planet formation scenario. 100 models are averaged for each plot. The survival probability increases as the time scale for migration decreases. The significant differences between the fate of the four planets are partially the result of the different resonances with the giant planet, and partially due to the random initial relative orbital phases.

net impulse varies depending on the velocity difference between the terrestrial planet and the giant planet and the distance at closest approach. If the planet remains in a Jovian-crossing orbit this can occur several times, exciting the orbit dramatically and possibly leading to the ejection of the terrestrial planet. Planets which experience orbital excitation due to the giant planet typically also acquire large orbital inclinations, as opposed to planets excited by other terrestrial planets which remain at low inclinations; similar effects were noted by Thommes et al. (2002) in simulations of the formation of Neptune and Uranus.

The dynamics are chaotic, and the ultimate fate of specific planets is highly dependent on initial conditions. However, once the Jovian-type planet has moved sufficiently close to the star it effectively decouples from any remaining bound terrestrial planets and the remaining planets settle into quasi-stable orbits. Longer-duration simulations will be necessary to adequately evaluate more fully the detailed long term stability of the ensemble of surviving systems; however, in real planetary systems other effects, including dissipative effects, and other outer planets, may change the orbital parameters of the outer terrestrial planets before significant long term dynamical evolution takes place.

For the 5×10^5 year integrations, the Jovian-type planet's increased migration speed caused fewer ejections (due to fewer crossings) and more total remaining terrestrial planets. For the 2×10^6 year integrations, this trend is reversed. The percentage of planets remaining declined from 40% for the 5×10^5 year integrations to 15% for the 2×10^6 year integrations, with an overall average of about 1/4 of terrestrial planets ending up in bound orbits outside the migrated Jovian-type planet, averaged over all three sets of integrations for the Solar System analog using constant migration (see Fig. 2 for a complete distribution of the three main simulation groups). The alternate planetary configurations from the Chambers models gave similar results, with a maximum survival rate as high as 35% for one configuration and a migration time scale of 10^6 years. As expected, using a variable migration model taken from Trilling et al. (2002), which starts with a fast linear migration and slows after $\sim 6 \times 10^5$ years, resulted in a higher survival rate for the Mars and Earth analogs (because of the faster initial migration) and a lower survival rate for the Venus and Mercury analogs (due to the slower migration rate a late times), averaging out to a similar overall survival rate.

Several interesting conclusions may, tentatively, be drawn from these results. First, despite expectations to the contrary, the migration of a giant planet does not

is the mass of the Jovian and M_* is the mass of the central star (Gladman 1993). After an impulsive perturbation the orbit has some final eccentricity, e, and semi-major axis, $a_f \gg a_i$, and necessarily $a_f(1-e) \approx a_i$. The orbital period is now typically 1-2 orders of magnitude longer than it was initially. On each return to periastron, the terrestrial planet has a renewed opportunity to interact with the Jovian, if it is still bound to the star. However, the probability of interaction is only $\sim r_H/2\pi a_i \sim 0.02$ per orbit crossing, and if migration is rapid the Jovian moves by r_H in orbital radius in $\sim 10^4$ years at $a_i \sim 1\ AU$, so there are only a small discrete number of occasions for interactions that could lead to ejection or collision before the Jovian migrates far enough in that it is decoupled from the new orbit of the terrestrial planet. If the terrestrial planets straddle the Habitable Zone when formed initially, then the final re-circularized orbits of a significant fraction of surviving terrestrial planets will be close to their initial orbits.

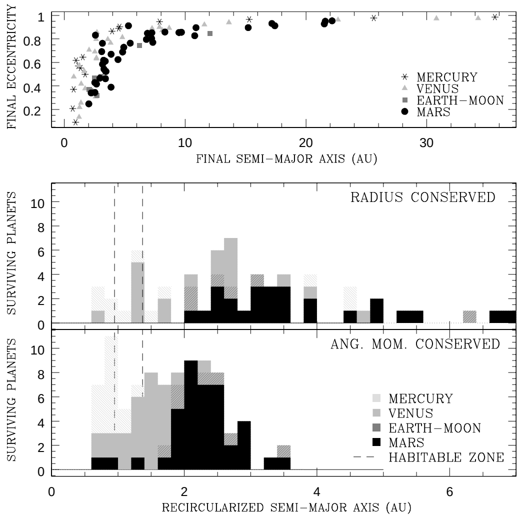

FIG. 3.— The upper plot shows semi-major axis vs. eccentricity for all the surviving planets in the 100 integrations with a migration time scale of 1×10^6 yr and a constant migration rate. The correlation between semi-major axis and eccentricity is simply due to the requirement that the final orbit pass through the point at which the impulse on the original orbit occurred. A slight trend with initial planet position can be seen. The lower plots show histograms of the theoretical final semi-major axes for planets coming within 7 AU only, in the 100 integrations after re-circularization due to dynamical friction has occurred. The middle plot assumes an upper limit where the semi-major axis is conserved after recircularization; 7% of the surviving planets are in the Habitable Zone. The lower plot assumes a lower limit of re-circularization with conservation of angular momentum; in this case 16% of the surviving planets would have semi-major axes in the Habitable Zone.

eliminate terrestrial mass planets from the inner planetary system. A significant fraction of terrestrial planets may survive the giant planet migration process, *if* the embryonic inner planets are in place before onset of type II migration. Therefore planetary systems may form and persist with a hot Jovian-type planet in a close orbit and terrestrial planets at farther distances. Future searches for Earth-like planets need not be restricted to planetary systems like our own. This is particularly true if migration occurs quickly, either due to massive protoplanetary disks or other migration effects. This could also have ramifications for systems without a close-in giant planet. If migration causes a giant planet to travel inwards and accrete onto the parent star, only terrestrial planets would be left in the outer system. Therefore, systems in which migration of the Jovian-type planets lead to the total destruction of the most massive members of the system could still contain terrestrial planets which survived the migration process and ended up in near-circular orbits in or near the Habitable Zone.

The semi-major axes and eccentricities of the remaining terrestrial planets span a large range, from less than 1 AU to greater than 30 AU and from 0.1 to almost 1.0 respectively (see Fig. 3). Orbital inclination is also generally large at the end of migration. Similar results were found for several test simulations using 100 asteroid-size particles, suggesting that the interactions with the giant planet are independent of planetesimal mass for low masses. Current calculations suggest *ab initio* planet formation cannot take place in the outer disk after migration (Armitage 2003). However, the presence of remaining planetesimals and circumstellar material in the disk will lead to strong circularization of the bound terrestrial planets due to dynamical friction and/or interactions with the remnant gas disk (Agnor & Ward 2002; Thommes et al. 2002). The outer bound terrestrial planets can settle back into near-circular co-planar orbits, even if the mass of material in the outer disk is inadequate to form terrestrial planets from material remaining after migration. Some incremental mass accretion may also occur. Planets with high eccentricities will tend to recircularize with minimal change in semi-major axis (for discussion see Thommes et al. (2002), Weidenschilling et al. (1997) and Wetherill & Stewart (1989)). Lower limits on post-recircularization orbital size can be found by assuming conservative re-circularization with negligible angular momentum evolution, where the final circular orbit has semi-major axis $a_c = a_f(1 - e^2) \approx a_i(1 + e)$. The outer disk may provide additional drag on the outer planets, leading to migration inwards; by inspection (Figure 3) modest drag will not decrease the fraction of planets that end up in the Habitable Zone and, if anything, will slightly increase the numbers. Assuming a solar-type star as the parent star and a Habitable Zone between 0.95 AU and 1.37 AU (Kasting et al. 1993), between 7% and 16% of the remaining planets in the 1×10^6 yr simulation would eventually reside within the Habitable Zone, which implies of order 1-4% of systems in which migration occurred would have a terrestrial mass planet in the Habitable Zone, assuming a pre-migration ensemble of terrestrial planets comparable to the Solar System.

This has very interesting implications for the existence of terrestrial planets, and specifically habitable terrestrial planets, in planetary systems with a migrating Jupiter-mass planet. Earth-like planets may persist in the Habitable Zone despite the rapid migration of a giant planet through the Habitable Zone during the formation phase. The critical result is that planetary embryos assumed to form before onset of migration can survive the migration process and persist as cores for terrestrial mass planets in the inner system, outside the orbit of the Jovian that migrated inwards. The postulated re-circularization phase, post-migration, involves interaction with primarily icy outer system objects; naively one therefore predicts significant volatile enrichment of the planets post-migration, possibly leading to a population of predominantly volatile-rich terrestrial planets (see Kuchner (2003) for a discussion of volatile-rich planets). Further research is required to explore the detailed interaction of the planets in the post-migration phase.

In conclusion, in a simplified dynamical model of a giant planet migrating through a stationary terrestrial planet system terrestrial planetary embryos will *not* be completely eliminated from a planetary system. During migration, terrestrial planets can cross the orbit of the migrating giant planet. The scattered planets have a significant probability of remaining bound to the central star, and may settle back into the Habitable Zone, even where post-migration ab initio formation of terrestrial planets is not possible.

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